2014

The New COAST Laboratory of Plymouth University: a World-Class Facility for Marine Energy

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http://hdl.handle.net/10026.1/16645

From Sea to Shore - Meeting the Challenges of the Sea
ICE Publishing

The New Coast Laboratory at Plymouth University: A World-Class Facility for Marine Energy

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Summary

During the development of coastal, ocean engineering and marine renewables technology, physical modelling must be undertaken. The new COAST laboratory at Plymouth University comprises two wave basins and two wave flumes that can all produce waves and currents together. Initial commissioning experiments of the facilities show that the design specifications were met in the majority of cases or exceeded. Despite the newness of the laboratory, experiments to investigate the motion response of a wave energy converter and to investigate wave impacts on moored structures have been undertaken in collaboration with both universities and commercial clients.

Introduction

Physical modelling plays a crucial role in the development and understanding of coastal and ocean engineering solutions and is also important to the development of marine renewable energy technology. It is in this context that Plymouth University, long renowned for marine science and engineering, has built its COAST (Coastal, Ocean and Sediment Transport) laboratory housed in the Marine Building, which was opened in October 2012 (www.plymouth.ac.uk/coast).

The laboratory is a relatively new facility, and much of the work completed to date has been related to the calibration and commissioning of its three main modelling facilities. This paper presents the laboratory and the results of some of the commissioning experiments, as well as examples of recent projects undertaken within it.

Reliable, efficient wave and tidal energy converters are a prerequisite if marine energy is to realise its potential and become a viable renewable energy resource (DECC, 2011). Laboratory testing is an essential part of technology development, which is defined as technology readiness levels (TRL) 3-5 according to the scale developed by NASA (Mankins, 1995). The TRLs, shown in Figure 1, describe the state of the technology at each stage and also the institutions likely to be involved. COAST is part of the South West Marine Energy Park, a collaborative partnership between local and national government, Local Enterprise Partnerships, technology developers, academia and industry. The South West MEP facilitates marine renewable energy technology developers moving opportunities from TRL 1 to TRL 7 (SWMEP, 2012). The COAST laboratory is supporting development of new technology up to TRL 5 and because experimentation is designed to be undertaken at intermediate physical scales, the development remains cost-effective.

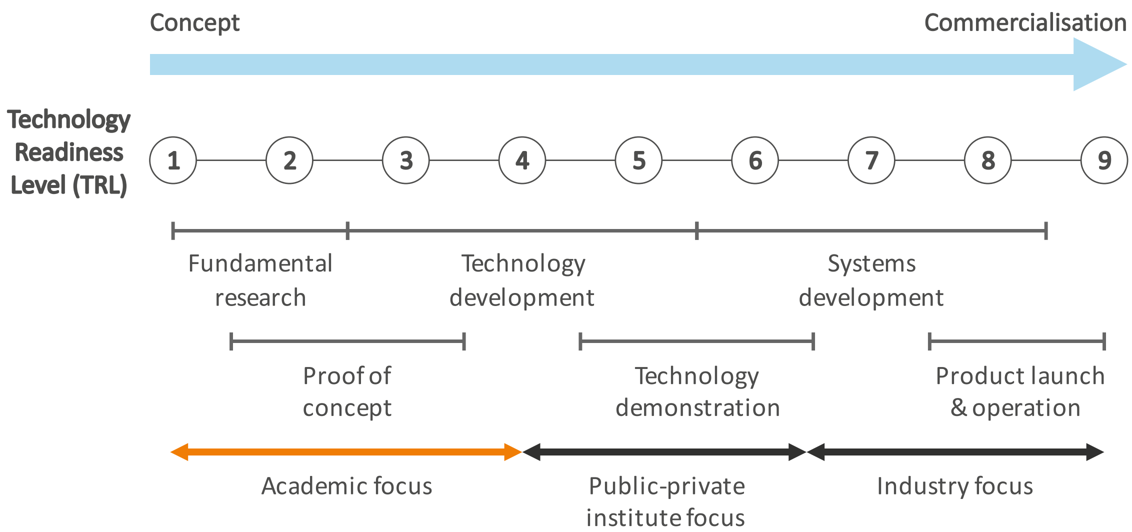

Figure 1 – Technology readiness levels describe the stages that new products must undergo from concept to commercialisation.

The COAST laboratory is also part of PRIMaRE, the Peninsula Research Institute for Marine Renewable Energy (www.primare.org), which was set up to assist businesses involved in marine renewable energy and to support Wave Hub. Wave Hub is a near-shore facility, located 16 km off the north Cornwall coast, which enables WEC demonstrators to be tested at sea at a grid-connected sea-bed installation. PRIMaRE and Wave Hub are also part of the South West Marine Energy Park:

The COAST Facilities

The COAST laboratory comprises a set of complementary modelling facilities: deep water and shallow water basins as well as 2D flumes, providing wave, current and wind generation capabilities. The facilities allow experiments to be conducted in the fields of coastal, ocean, and sediment transport science and engineering. With these characteristics and its suite of specialist instrumentation, the COAST laboratory is suited for a broad range of physical model tests: from the newest wave and tidal energy converter designs through optimisation of coastal structures to movable-bed models.

Ocean Basin

The Ocean Basin, Figure 2, is the largest tank in the laboratory and offers a range of operating parameters. It is over 32 m long from the paddles to the back wall and 15.6 m wide.

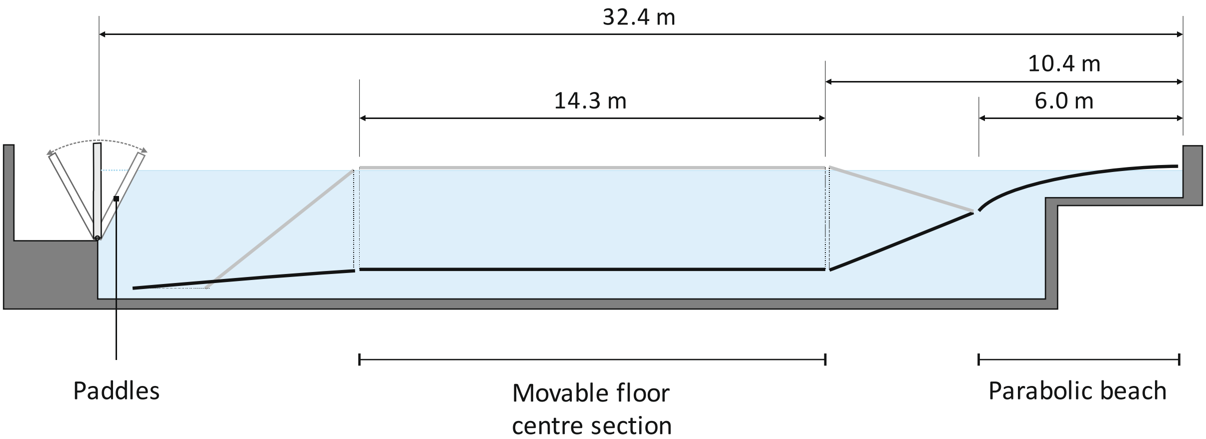

Figure 2 – Cross-section view of the Ocean Basin. The floor is shown at full depth (black line) and fully raised (grey line above water surface). When the floor is at full depth, the water across the central section is 3 m deep. The current inlets are positioned in front of the paddles and along each longitudinal wall of the basin.

The floor is mounted on scissor jacks allowing it to be operated at any depth up to 3 m or with a slope of up 1:20. The wavemakers of the Ocean Basin, which are situated along the full width of the tank, are dry-backed, hinged paddles. The 24 paddles are individually force-controlled which means that as well as producing the waves, the paddles absorb the reflections that return to the paddle face. Currents can be run both longitudinally and transversely instead of, or in addition to, the waves.

The Ocean Basin paddles are designed to produce regular and irregular waves. The specified height of the regular waves is up to 0.85 m depending on the period; at short periods the waves will break, limiting the height and at long periods, the height is limited by the stroke of the paddle. Figure 3 shows the results of the preliminary experiments to determine the maximum wave height at a given period. The measured values in Figure 3 represent the highest of three input wave heights at each period and it may be that the maximum has not yet been achieved.

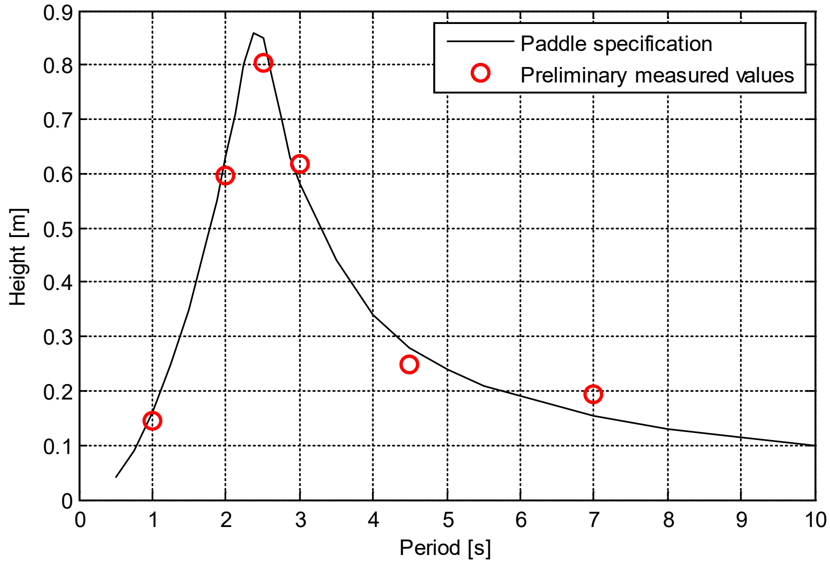

Figure 3 – Preliminary experiments showed that the wave height was within 10% of the design specification of the paddles in the majority of cases.

The measured wave heights were within 10% of the specification in the majority of cases. Figure 3 shows that the deviation from the paddle specification was greatest at longer periods. In these cases, the paddle stroke was the limiting factor for the maximum wave height. Since testing the system to its operational limits forms part of the on-going work, it is anticipated that the input settings to the system can be adjusted to make full use of the total paddle stroke. Future experiments will allow the maximum wave height to be calculated within a 95% confidence interval.

The Ocean Basin in the COAST laboratory is the only facility in the UK to offer deep-water testing of marine renewable energy technology under combined wave and current forcing conditions with waves and currents at any angle to the device. The longitudinal current speeds in the Ocean Basin depend on the depth of the floor. The design criterion was to have a mean longitudinal flow speed of 0.2 m/s at the surface when the floor was lowered to 2.0 m depth. Measurements have shown that along the centre-line of the Basin, the surface speed was 0.275 m/s in 2.0 m of water. With a water depth of 1.0 m, surface flow speeds of up to 0.45 m/s were recorded.

Coastal Basin

Sediment transport and coastal structures can be studied in the shallow-water Coastal Basin, which is especially important in the evaluation of breakwater structures. As with the Ocean Basin, the Coastal Basin is a versatile facility. The basin is 13.5 m long from the paddles to the end of the beach and is 10 m wide, Figure 4. Waves are created using five modules of four paddles. Each paddle is an individually force-controlled piston paddle that can actively absorb any reflected energy not dissipated by the beach.

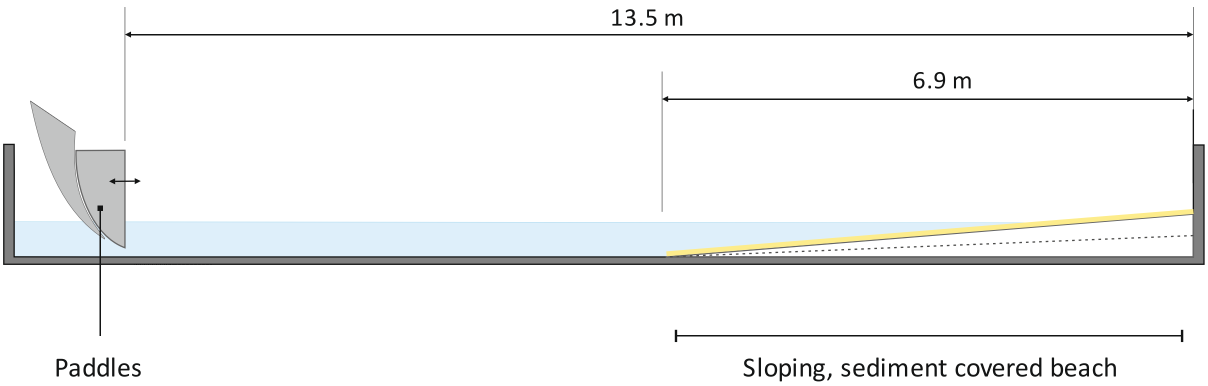

Figure 4 – Cross-section view of the Coastal Basin. The nominal depth of the tank is 0.5 m. The beach section may be positioned to provide base slopes of 1:10, as shown, or 1:20.

An adjustable shore platform provides a starting bed slope of 1:10 or 1:20, with the toe of the platform about half way along the basin. The sloping platform can be used as a base for fixed-bed or mobile-bed studies. If desired, a beach can be added to the basin.

The water movement options are numerous. A variety of waves can be run (monochromatic, irregular, short-crested, long-crested) all with the option of adding a transverse current. The design specifications of the Coastal Basin state that regular waves of up to 0.32 m (exceeding that which is appropriate for 0.5 m water depth), and uniform currents of up to 0.5 m/s can be generated; continuing experiments will verify these values.

Sediment Flume

For two-dimensional studies of sediments, coastal structures or wave-current interaction, the sediment flume can be used. Waves are generated along the 35 m flume by the force-controlled piston paddle, as shown in Figure 5. At either end of the flume the inlet/outlet points for the recirculating current are found. Flow of up to 0.5 m/s can be generated either in the direction of travel of the waves or opposing it. This figure is likely to be exceeded since the speed of the flow at the surface was found to be 0.24 m/s with the motor running at 24%.

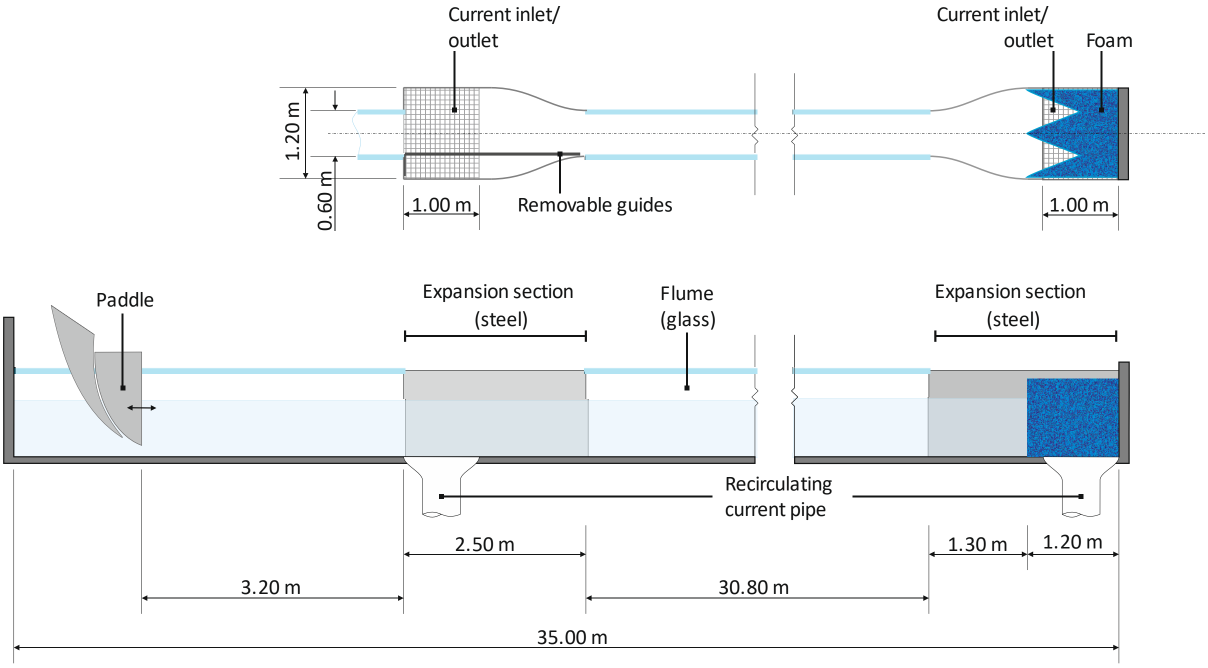

Figure 5 – Cross-sectional view and partial plan view of the Sediment Flume. The nominal depth of the tank is 0.75 m. The guides (only one shown) in the first expansion section are removed when the currents are run.

Commissioning the Facilities and Example Experiments

The COAST laboratory, being a new facility, is still undergoing commissioning experiments and while guidelines for the types of experiments necessary exist, many of them focus on the methodology of testing new WECs rather than the facilities themselves. The Marine Renewables Infrastructure Network for Emerging Energy Technologies (MARINET), of which Plymouth University is a partner institution, states that there is no proper consensus on appropriate test methodologies and practices (MARINET, 2013). With this in mind, we present some of our initial work. Since the objectives of experiments undertaken in the laboratory are varied, even within each facility, the general experimental methods and common features are presented.

Typical Experimental Methods and Analysis

The wavemakers in the three experimental facilities are manufactured by Edinburgh Designs Ltd. (EDL), UK, and are run with their own software: Wave Synthesiser and OCEAN. The wave synthesiser allows a range of uni- directional and multi-directional spectral sea states to be generated as well as many “effects” and monochromatic waves.

The elevation of the free surface is measured with twin-wire resistance wave probes that are connected to EDL wave hubs which are in turn connected to a computer running the EDL software. From the OCEAN software client, the probes can be calibrated. Typically, the probes are calibrated at the beginning of each experimentation day after the water in the tanks has been mixed to ensure homogenous conductance and then allowed to settle.

Calibration of the probes in the sediment flume at the beginning and end of each experimental session, for example, revealed that the values did not change sufficiently to warrant more frequent calibration (the maximum standard deviation of 7 repeated calibrations on 10 different probes was less than 3% of the mean gauge reading).

Data are recorded at 128 Hz via the EDL hubs and may comprise probe voltage, calibrated surface elevation, information concerning the paddle position and paddle force together with data captured from other connected devices such as acoustic Doppler velocimeters, high-speed cameras, the Qualysis 6 degree of freedom motion-capture system and particle image velocimetry.

Analysis of the hub data is most often achieved in MATLAB and wave heights and periods are calculated using time-series analysis. Unless otherwise specified, wave statistics presented in this paper were calculated using the zero up-crossing method.

Calculation of Reflection Coefficients in the Ocean Basin

Owing to the different types of experiments that can be performed in each basin, they all have different beach structures. The beach of the Ocean Basin is a parabola covered with glass reinforced plastic and metal foam and the Coastal Basin currently has a sloping bed covered with sand sediment.

For the experiments undertaken in the Ocean Basin, it is desirable for the beach to dissipate as much of the incident wave energy as possible; to avoid contamination of data concerning a structure in the middle of the basin. The reflection coefficient of a basin is defined as the reflected wave height as a proportion of the incident wave height, at a particular period. To be able to differentiate between incident and reflected waves, two or three probes can be used with information coming from a combination of wave heights and phase angles and the three-probe method was chosen for this purpose as it is more accurate (Isaacson, 1991).

Monochromatic waves were run at 13 periods between $T = 1.26$ s and $T = 4.86$ s and at three different wave heights ($H = 0.133$ m, 0.200 m and 0.267 m). Between runs, the tank was left to settle for approximately six minutes. Wave probes were placed along the longitudinal centreline of the tank with the first probe at a distance of 15 m from the paddles; the second and third probes were 0.4 m and 1.2 m respectively from the first probe. The information necessary to differentiate the waves comprised three-wave heights and two phase angles, which were computed from Fourier components resulting from a fast Fourier transform (FFT). This information was used in a least-squares fit to differentiate between the two waves as described by Mansard and Funke (1980).

The amplitude had little effect on the value of the reflection coefficient, C_R, however the size of the wave reflected was influenced by the wavelength; typically the value of C_R was larger when the waves were longer. Figure 6, shows the reflection coefficient plotted as a function of the period. The reflection coefficient showed a large increase in value at periods between 2.5 s and 3.5 s and it appeared that there was another sharp increase at periods greater than 4.0 s.

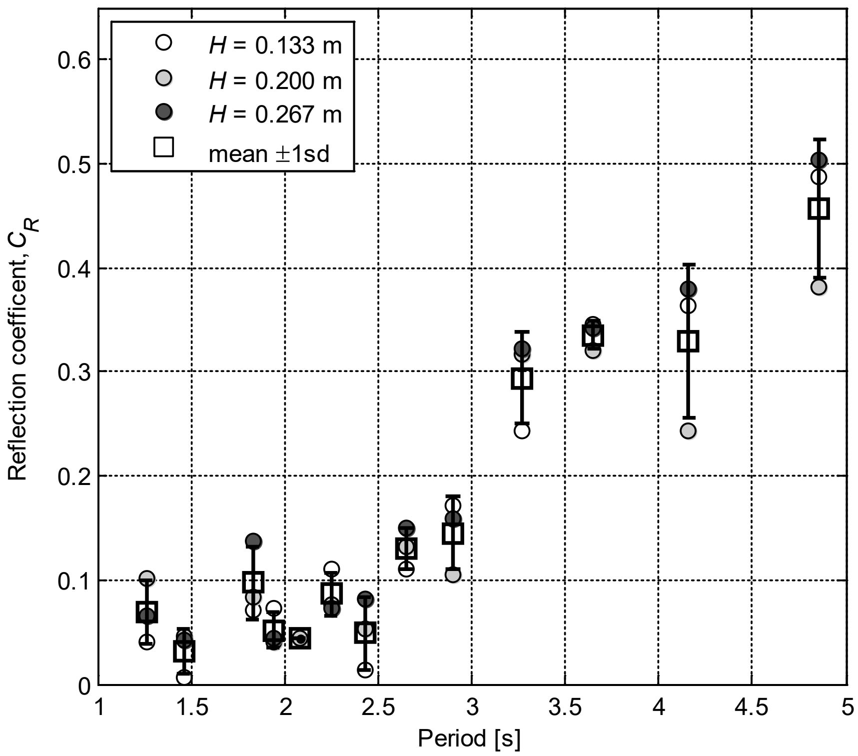

Figure 6 – Reflection coefficients calculated using a three-probe method for a range of periods and three wave heights in the Ocean Basin, plotted as a function of the period.

Directional Spectra in the Coastal Basin

The random waves that occur at sea can be modelled by spectral representations based on the statistical variability of the wave properties (Donelan *et al.*, 1996). The spectral representations can then be used in facilities such as the Coastal Basin to investigate waves and devices in a controlled environment. To analyse the resulting sea-state, several methods may be used and one such method is the wavelet directional method (WDM).

As part of a larger experimental series, a JONSWAP spectrum was generated in the Coastal Basin, with a peak spectral period of T_p = 0.8 s and a significant wave height of H_s = 0.031 m. A spreading function of $\cos^N(\theta)$ was applied to the spectra with larger values of N producing narrower spectra. Wave probes were arranged in an array to measure the directional components. The array consisted of six probes: five creating a regular pentagon that lay on the circumference of a 0.25 m radius circle and one probe at the circle's centre. Data were recorded for fifty minutes.

Figure 7 shows the directional spectra and the normalised energy plots for two different spreading values. The normalised energy plots show the cross-sectional view through the directional spectra at their peak energy values. The results show that for broad spectra, the measured energy is narrower than that given analytically. This was expected, since the wavelet directional method was shown by Donelan *et al.* (1996) to underestimate directional spreading at higher frequencies. The alternative would be to use the maximum likelihood method, which has been described as the most accepted method despite its consistent overestimation of spreading (Donelan et al., 1996).

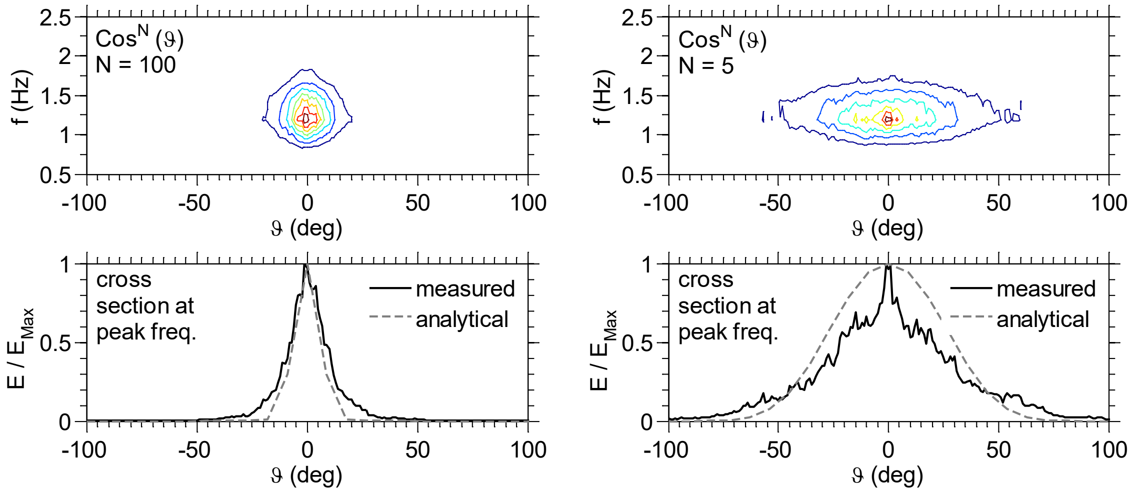

Figure 7 – Frequency-direction spectra show the difference between narrow (left) and broad (right) spectra and the energy plots show the difference between the measured values and analytical results for directional seas (JONSWAP) in the Coastal Basin.

Calibration of the Sediment Flume

Following the example of Iglesias (2001), the Sediment Flume was calibrated using a fixed value of the ratio $2e/h$, where $2e$ represents the paddle stroke and h the undisturbed water depth (0.75 m). Two values of the stroke ratio, $2e/h$, were used: 0.1, referred to as the short paddle stroke; and 0.3, the long paddle stroke. Monochromatic waves were produced at periods, T, between $T = 0.826$ s and $T = 3.32$ s. The lower limit of the period was chosen to be on the limit of theoretical breaking height (Miche, 1951), and the upper limit corresponded to the boundary between transitional and shallow depth according to the wave dispersion equation.

At each value of period, the input wave height was calculated using the Biesel transfer function (Pilch, 1953), given in Eq.(1), in which the ratio of the input wave height, H, to the paddle stroke, $2e$, is a function of the water depth, the wave number, k, and the distance between the base of the tank and the paddle, δ (0.15 m).

$$\frac{H}{2e} = \frac{2\sinh^2(kh) - 2\sinh(k\delta)\sinh(kh)}{\sinh(kh)\cosh(kh) + kh} \quad (1)$$

Seven probes were used to measure the height of the free surface: one 3 m from the paddle and two groups of three probes, with the centre probe at $L/3$ m and $2L/3$ m from the paddle, where L is the total length of the flume, 35 m. The distance between the first probe and the centre probe in a group was different from the distance between the centre probe and the last probe in the group. This unequal spacing allowed a three-probe reflection analysis to be undertaken and the distance between the probes was based on the ideal separations given in Isaacson (1991). Waves were run for two minutes each and the tank was allowed to settle for 10 minutes between runs.

Figure 8 shows the typical time histories of the probes: the top trace represents the probe closest to the paddle and the bottom trace represents the probe furthest from the paddle. The time taken to reach the next probe down the tank was not constant owing to the unequal probe spacing along the tank.

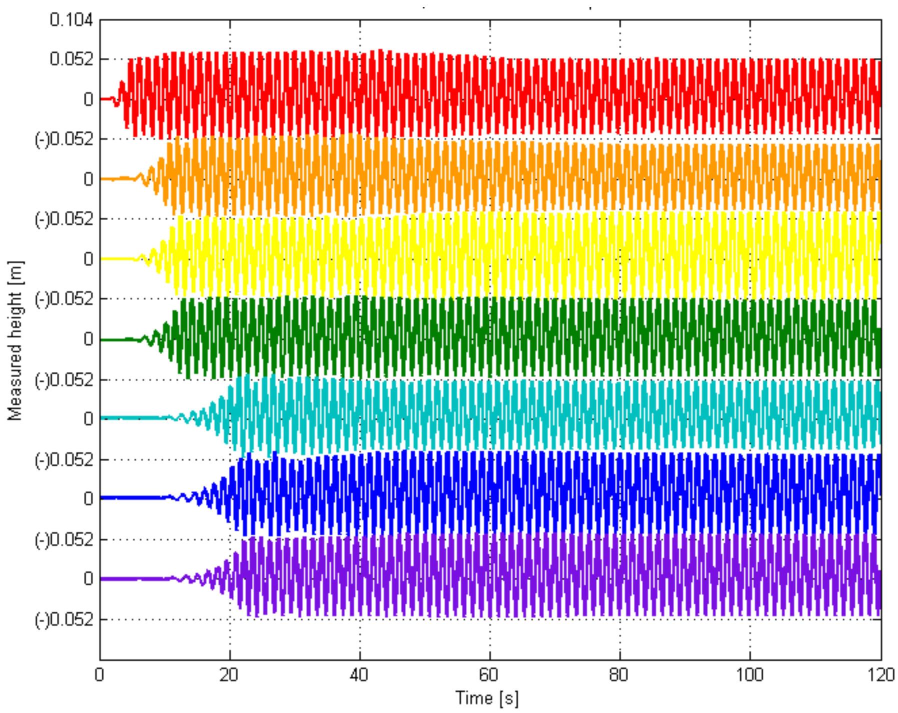

Figure 8 – Time histories of the probes during one of the short stroke experiments. T = 1.32 s with an input wave height, H = 0.104 m.

Before the reflection analysis was undertaken, the wave heights were calculated using the zero up-crossing method on a windowed portion of the data and the first two seconds of data were ignored as these corresponded to the paddle ramp-up time. The wave celerity was calculated and used to predict the time that a reflected wave would be registered by the first probe and this time was verified by consulting the time histories of the probes.

The mean heights of the waves accorded well with the input wave heights, although this accordance was generally better for longer periods, i.e. when the waves were not as steep. This is shown in the left panel of Figure 9 in which the input and measured wave heights are plotted as a function of period, with steepness contours overlaid.

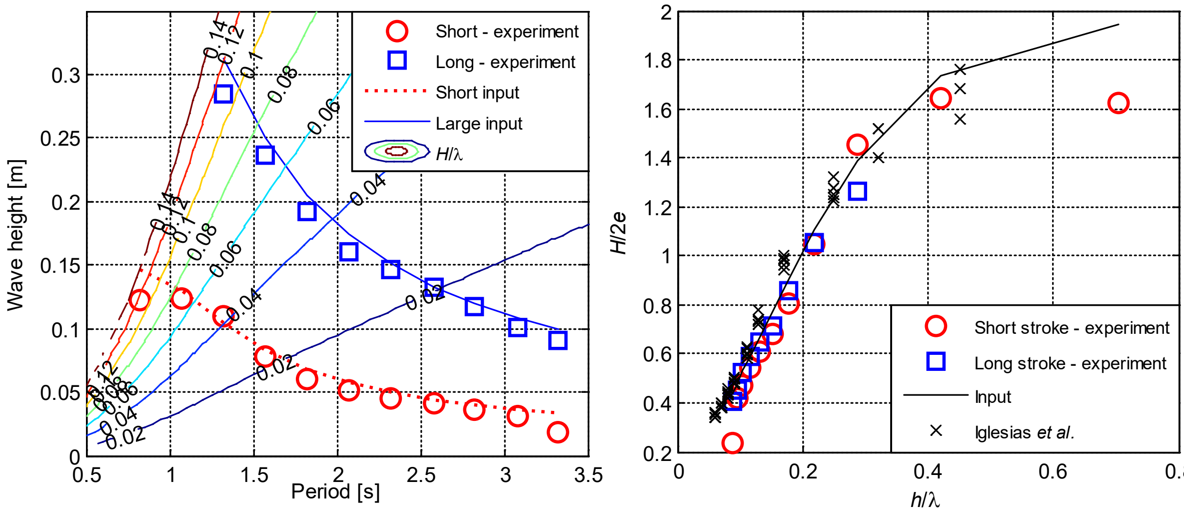

Figure 9 – Both long and short stroke experiments accorded well with the input wave height (left), and with other experimental data (right). When the steepness (H/λ) was high, which corresponded to a large depth-normalised wavelength, h/λ, the deviation of the measured wave heights was large.

The right-hand panel in Figure 9, in which the wave heights have been normalised by the paddle stroke (ordinate) and the abscissa represents the quotient of water depth and wavelength (h/λ), shows that the deviation of the data from the input values was comparable to other experiments.

Testing Wave Energy Converters

Part of the motivation for the construction of the COAST laboratory was to provide a suitable environment for the testing of wave energy converters (WECs) and moored structures, typically at a medium scale, and, importantly, arrays of devices as smaller scales. Physical modelling of WECs is pertinent since, for example, the mooring lines are often designed so that they act with the device to ensure a dynamic response that provides maximum efficiency of the system. Such analysis is not always feasible numerically and any numerical models must be extensively validated with physical testing (Rawlings and Klaptocz, 2010).

One such WEC tested in the Coastal Basin was that of Offshore Wave Energy Ltd (OWEL). Experiments were undertaken to investigate the motion response of a 1:56 scale model of the device and to quantify the response amplitude operators in the three most important degrees of freedom for power production: surge; heave and pitch (Leybourne *et al.*, 2011). This was done using a six degree of freedom motion tracking system (Qualysis). It was found that peak loads occurred at the largest and steepest wave combination owing to high rotational velocities in pitch coupled with large surge displacements.

Extreme event modelling is another important concern for WECs. In the Ocean Basin, the X-MED project (EXtreme Loading of Marine Energy Devices), has been running to measure the loads and responses of a taut moored floating body due to steep and breaking wave impacts, in both long crested and directional sea states. The principal goal of Plymouth University’s contribution to the X-MED project is to use the results of the experiments to validate numerical models created in STAR-CCM+, a commercial volume of fluid CFD solver.

Conclusions

This paper presents details of the COAST laboratory facilities and some examples are given describing the commissioning experiments and early project work that have been a major part of the work undertaken to date.

The calibration of the Sediment Flume, the reflection analysis of the Ocean Basin beach and the analysis of directional spectra in the Coastal Basin have highlighted the versatility of the COAST facilities along with providing some insight into the commissioning process of a new laboratory. Further commissioning tests are underway to characterise the longitudinal and transverse currents and wave generation capabilities in each of the new facilities.

As a University Laboratory, COAST is intended for research, teaching and commercial work, and the number and variety of projects already being undertaken in the laboratory is testament to the commercial and research links that the laboratory has created and consolidated, building on the reputation of marine science and engineering at Plymouth University.

Acknowledgements

The X-MED project is an EPSRC funded, SuperGen UK Centre for Marine Energy Research project and is a collaboration between the Universities of Manchester, Edinburgh and Plymouth and the Scottish Association for Marine Sciences. Keri Collins was directly supported by the School of Marine Science and Engineering of Plymouth University.

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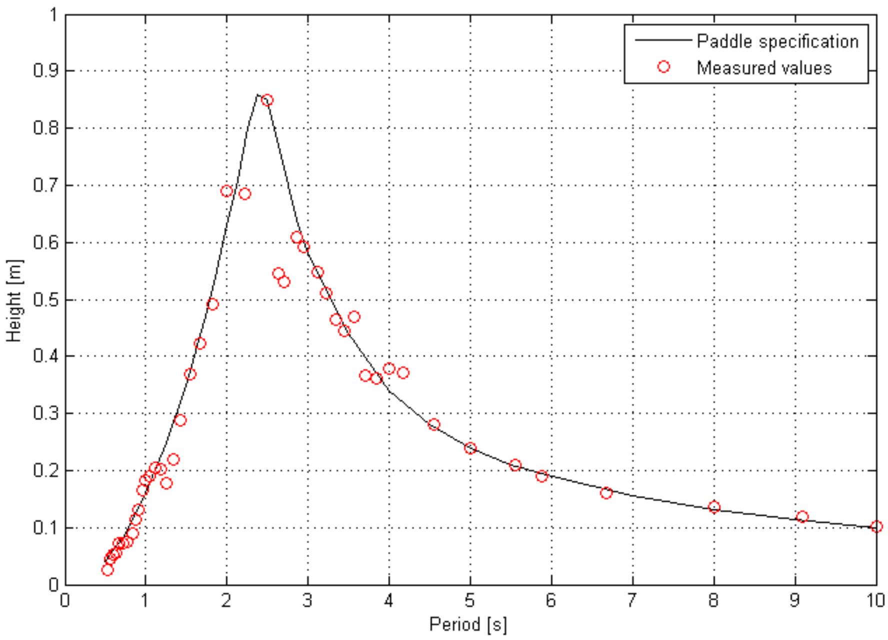
ICE Discussion questions

Author: Keri Collins
Discussion Contributor: William Allsop
Question / Contribution:

1. You imply that some (all) of the performance graphs in the paper are out-of-date. Please add to the discussion your updated performance results
2. You have a very sharp slope transition in your floor. Will this not significantly distort the breaking, see especially Allsop et al (2001).

Author's answer:

Recent measurements of the Ocean Basin's paddle capabilities (regular waves) are shown in the Figure below:



Updated performance graphs will be made available on the group's website (www.plymouth.ac.uk/coast) when possible.

With the ability to raise the floor to any working depth from 3.0 m to the free surface, Professor Allsop is correct that we must be mindful of the floor's influence on the wave breaking. The diagram of the Ocean Basin, presented in the paper (Figure 2) is drawn (where possible) to scale. When the floor is fully down (3.0 m), this results in a slope of approximately 1:12, however as the floor is raised, this slope will increase to approximately 1:1.25 (as shown in Figure 2). The floor depth is input to the OCEAN software (Edinburgh Designs Ltd.) that controls the motion of the wave paddles and so the geometry of the basin is accounted for in the wave paddle transfer functions, which should mitigate the effects of the slope. Work to characterise the wave conditions at all floor depths is on-going.